VISITING TOGA'S PAST

David Halpern
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109-8099
tel: 818-354-5327
fax: 818-393-6720
email: halpern@pacific.jpl. nasa.gov

ABSTRACT

The origin of the Tropical Oceans Global Atmosphere (TOGA) Program was closely related to the response of global atmospheric circulation to sea surface temperature variations in the tropical Pacific Ocean, which is evident by the El Niño phenomenon. During two decades before the 1985 start of TOGA, advancements in scientific understanding of the tropical ocean and global atmosphere and advancements in technology provided strong foundations for TOGA. By the early 1980s, research had demonstrated a strong linkage between tropical SST variations and global atmospheric circulation, and discussions of an international ocean-atmosphere program had begun. Probably the single most important event leading to the creation of TOGA was the unannounced arrival in 1982 of the largest El Niño in a century.

1 INTRODUCTION

The Tropical Oceans Global Atmosphere (TOGA) Program began January 1985 and ended December 1994. TOGA scientific objectives (Table 1) were developed in 1983 and 1984 in accord with ideas and technology available at the time. What were the scientific ideas and what was the level of technology at the beginning of TOGA? What was the progression of scientific ideas and technology that formed the basis of TOGA? Were factors other than science important in the development of TOGA? These questions will be explored in this paper.

Modern day ocean sciences begins with the 1872-1876 voyage of the H. M. S. *Challenger*. When the *Challenger* sailed from Honolulu to Tahiti along approximate] y 150"W during August and September 1875 (Thurman, 1991), no El Niño was occurring (Quinn *et al.*, 1987). Even if there had been an El Niño, scientists aboard the *Challenger* would not have recognized characteristics of the warm-water phenomenon. At that time, the El Niño was thought to be a relatively small scale phenomenon associated with the coastal regions of South America and no sea surface temperature climatology existed in the central Pacific to determine if the August - September 1875 sea surface temperatures were different than normal.

Not until the 1960s did scientists consider the El Niño phenomenon off South America to be part of a global phenomenon. Had El Niño continued to bc associated primarily with coastal South America, there would not have been a TOOA Program.

2 El NIÑO AND TOOA

2.1 1957-1958 El Niño

Each year, beginning in 1950, the California Cooperative Oceanic Fisheries Investigations make extensive biological, chemical and physical oceanographic measurements off the west coast of North America. As a result of the time series, unusual conditions were noted in the circulation off California during 1957 and 1958. However, unusual environmental conditions during 1957 and 1958 were not confined to the California Current, but were observed throughout the Pacific (Sette and Isaacs, 1960). For example, Canton Island, usually dry, was covered with vegetation; Hawaii had its first recorded typhoon; warm water invaded the coastal area of Peru; sea ice at Point Barrow retreated very early; the Aleutian Low was intensified; winds along California were weak; and sea surface temperatures over the eastern North Pacific were 3°C higher than normal.

The anomalous oceanographic and meteorological conditions that occurred over a large portion of the globe during 1957 and 1958 remained unexplained for nearly a decade. Then, Bjerknes (1966) proposed a novel idea that the appearance of warm water off the coast of South America was not caused by local ocean-atmosphere interactions, but was produced by an invasion of warm water from elsewhere. He speculated that the warming of the tropical Pacific from South America to the mid-Pacific was caused by a reduction of easterly winds. The subsequent increase in the zonal pressure gradient along the equator would allow water above the thermocline to flow east ward. In addition to heat advection from the western warm-water pool, the near-surface temperature in the eastern tropical Pacific would also increase because of a reduction in equatorial upwelling. He proposed that an anomalous atmospheric heat source in the tropical East Pacific would alter the Hadley circulation, including a strengthening of the Aleutian Low and a weakening of the Icelandic Low. The primary triggering mechanism of the temperature anomaly in the East Pacific remained a mystery.

Rowntree (1972), while visiting the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL), used the newly developed GFDL atmospheric general circulation model to substantiate the Bjerknes (1966) hypothesis about teleconnections between a sea surface temperature anomaly in the eastern tropical Pacific and middle latitude atmospheric conditions. The successful numerical experiment confirmed Bjerknes' hypothesis. Rowntree's experiment, which was not realistic because it used a hemispheric model with a wall at the equator, was followed by other numerical simulations, which did not employ the artificial geometry at the equator (Julian and Chervin, 1978; Keshavamurty, 1982; Shukla and Wallace, 1983; Blackmon *et al.*, 1983), to demonstrate the sensitivity of global atmospheric general circulation model simulations to the magnitude and location of prescribed anomalous sea surface temperature patterns in the tropical Pacific. The degree of predictability of global atmospheric circulation caused by tropical Pacific sea surface temperature variations became a TOGA objective.

2.2 1972-1973 El Niño

The El Niño of 1972-1973 had a great influence upon the price of agricultural products in many countries, including the United States (U. S.), because the Peruvian fishery catch, which at the time was the world's largest, dropped from 12. million tons to 2 million tons. Nearly all of the Peruvian fishery was ground into fish meal and distributed worldwide as a protein source for poultry and livestock. The alternate source of protein for animals was soybean, in which the largest supplier was the U. S. where the crop in 1973 was severely damaged because of heavy rains. Whether the large rain amount could be attributed to the El Niño remains unknown.

It seems fortuitous that two to three years before the. onset of the 1972-1973 El Niño, there was a resurgence of scientific interest in theoretical aspects of equatorial circulation. A previous burst of activity occurred in the 1950s after the 1952 discovery of the Equatorial Undercurrent

(Cromwell et *al.*, 1954). At that time, the explanations assumed steady-state motion (Deep-Sea *Research, 6, 1960, 263-334).* The renewed interest in equatorial ocean circulation focused on time-dependent motions. Blandford (1966), in the case of the ocean, and Matsuno (1966), in the case for the atmosphere, were first to examine the theoretical aspects of time-dependent motion along the equator. Moore (1968) first explained the dynamics of the Kelvin wave along the equator, but the result was not widely available for nearly a decade (see Moore and Philander, 1977). Lighthill (1969) provided the first theoretical foundation for the generation of low-latitude ocean currents driven by non-steady winds.

The 1972-1973 El Niño created a burst of scientific activity on the dynamical behavior of warm water episodes in the eastern tropical Pacific. Godfrey (1975) first proposed that an internal downwelling equatorial Kelvin wave, which would be created when an easterly wind stress had decreased, would signal the arrival of warm water in the eastern Pacific or El Niño conditions. Hickey (1975) showed that fluctuations of surface wind stress, sea level, and sea surface temperature were highly correlated in the equatorial Pacific, but was unable to describe a cause-and-effect relationship between the variables, perhaps beca use she seemed to be unaware of the work of Godfrey (1975). The next year, Hurlburt et *al. (1976)* and McCreary (1976) quantitatively described many features of the equatorial downwelling Kelvin wave that would be produced by a reduction in the easterly wind. In addition, McCreary (1976) demonstrated that temporal variations of the wind stress within 5° of the equator were substantially more important in creating equatorial Kelvin waves that the wind stress between 5° and 20° from the equator. McCreary's (1976) result had important consequences on the implementation of the TOGA moored-buoy array (Hayes *et al., 1991).*

Wyrtki (1975) provided a possible mechanism for tile 1972.-1973 El Niño by combining the conceptual model by Bjerknes (1966), theoretical result from Godfrey (1975), observational results from Hickey (1975) and Ramage (1975), and his observation of an important characteristic about the surface wind stress. Wyrtki (1975) reported that a period of stronger-than-normal easterly winds would buildup excessive warm water in the western Pacific, which would increase the magnitude of the east-west slope of sea level along the equator. Wyrtki (1975) speculated that upon relaxation of the easterly wind stress, the warm water would flow eastward along the equator as a Kelvin wave, and the thermocline in the eastern Pacific would deepen, allowing warm water to accumulate.

Three questions remained about the origin of El Niño episodes. Why do easterly wind anomalies occur for periods of several months in the central and eastern tropical Pacific? Is the strength of the natural variability of surface winds sufficient to create Kelvin waves? Do wind-generated Kelvin waves exist in the equatorial Pacific? The first question was not answered until the beginning of TOGA when El Niño was described as a coupled ocean-atmosphere system (Cane and Zebiak, 1985; Battisti, 1988), and not as a response of the ocean to variable winds, nor as a response of the atmosphere to variable SST. TOGA firmly established the belief, which was first proposed by Bjerknes (1966), that seasonal-to-interannual climate variability is neither strictly atmospheric nor strictly oceanic forced but is the result of coupled ocean-atmosphere interactions (Neelin et. *al.*, 1994). Answers to the other two questions required knowledge of the space-time structure of surface wind stress. In the middle 1970s, James O'Brien extended the Wyrtki and Meyers (1976) climatological-mean monthly wind stress by initiating an operational long-term monthly surface wind stress data product (Stricherz *et al.*, 1992). Busalacchi and O'Brien (1981) used these observed winds with a shallow-water model ocean to demonstrate that equatorial Kelvin waves could have deepened the thermocline in the eastern Pacific during the 1964-1965 El Niño. The use of a relatively simple model to explain thermocline variations in the eastern Pacific to wind variations in the central Pacific was a major accomplishment. Furthermore, researchers now had an ocean model for studies of the equatorial thermocline.

Missing from studies of the onset of warm events in the eastern equatorial Pacific was observational evidence of wind-generated equatorial Kelvin waves. First observations of wind-driven Kelvin wave propagation along the Pacific equator occurred in 1980 (Knox and Halpern, 1982; Eriksen *et al.*, 1983).

2.3 1976 El Niño

The 1976 El Niño, while moderate in intensity (Quinn *et al.*, 1987), had a profound effect upon U.S. society because of its association with extreme cold weather in the northeastern portion of the country where river transportation of heating fuel was halted by ice (Canby, 1977). Intensification and southward movement of the Jet Stream was associated with a low Southern Oscillation Index (Horel and Wallace, 1981) and with the Pacific/North American (PNA) teleconnection pattern (Wallace and Gutzler, 1981), both of which are strongly correlated with high sea surface temperatures in the tropical Pacific Ocean. For tropical sea surface temperatures to influence middle latitude atmospheric circulation, the tropical limb of the Hadley circulation must be altered. Gill (1980, 1985) suggested an explanation of the enhanced heating of the tropical Pacific atmosphere produced by increased sea surface temperatures in the tropical Pacific, including observed longitudinal migrations of both features. Wave processes were proposed to explain the teleconnections between sea surface temperature variations in the tropical Pacific and atmospheric circulation in middle latitudes (Hoskins and Karoly, 198 1; Webster, 1981).

Sea surface temperature anomalies in the North Pacific, which Narnias (1969) had used to make one- season forecasts of winter conditions over North America, were judged to be of lesser importance for atmospheric teleconnections compared to tropical sea surface temperature variations. For example, Chervin *et al. (1976)* could not simulate an adequate downstream teleconnection between North Pacific sea surface temperature anomalies and atmospheric temperature anomalies over North America. In addition, the statistical foundation for North Pacific sea surface temperature variations occurring before North Pacific sea level pressure variations was weak (Davis, 1978). Barnett (1981) showed that tropical Pacific sea sulfate temperatures were superior as predictors of North American air temperatures than mid-latitude Pacific sea surface temperatures. Thus, there was increased emphasis upon the study of tropical sea surface temperature variations and their influence upon global atmospheric circulation.

By the late 1970s, the association of tropical Pacific warm sea surface temperature episodes with North American seasonal climate and the appearance of a hypothesis about a generation mechanism of El Niño resulted in new oceanographic and meteorological programs in the tropical Pacific. The North Pacific Experiment (NORPAX), which was primarily funded by the U.S. National Science Foundation (NSF), expanded its objectives to include ocean-atmosphere interactions in the central tropical Pacific. In the middle 1970s, Klaus Wyrtki took over the maintenance of the island sea level gauge network from NOAA, and rapidly expanded the network throughout the tropical Pacific for studies of climate variations (Wyrtki, 1979). In the late 1970s, the NORPAX Program, in collaboration with institutions in Australia and New Caledonia, expanded the North Pacific SOP XBT project into the tropical Pacific (White *et al., 1985).* The 1979-1980 NORPAX Hawaii-to-Tahiti Shuttle Expedition measured for the first time the annual cycle of oceanographic conditions in the tropical *central* Pacific Ocean (Wyrtki and Kilonsky, 1984). This occurred 100 years after the voyage of the *Challenger,* illustrating the absence of repeated subsurface oceanographic observations in the vast interior of the Pacific Ocean until the)970 -1979 International Decade of Ocean Exploration. A legacy of the innovative ideas about tropical ocean circulation that emanated from NORPAX was the continuation of many measurements in the central equatorial Pacific under the auspices of the Pacific Equatorial Ocean Dynamics (PEQUOD) Experiment. Further to the east, near 110"W, the NOAA Equatorial Pacific Ocean Climate Studies Program (EPOCS) began in 1979 a long-term study of equatorial Pacific ocean-atmosphere interactions and their influence upon global climate.

The late 1970s and early 1980s were associated with a great increase of empirical large-scale ocean-atmosphere studies employing a new computer-readable compilation of global marine observations, some dating to the previous century. The data set subsequentl y became the Comprehensive Ocean-Atmosphere Data Set (COADS) (Woodruff *et al., 1987).* Examples of results emanating from pre-COADS were the description of an average El Niño (Rasmussen and Carpenter, 1982) and the influence of SST fluctuations in the equatorial zone near 130°W upon global atmospheric variables at 200 hPa (Pan and Oort, 1983). In addition to the research about tropical Pacific SST and atmospheric circulation, in the late 1970s the Soviets had initiated a series of experiments, both numerical and observational, to reveal the degree of sensitivity of atmospheric circulation over eastern Europe to SST variations in the tropical Atlantic. These kinds of studies, coupled with the progress being made to understand ocean dynamics of equatorial SST, prompted, in the early 1980s, discussions within the Global Atmospheric Research Program (GARP) to initiate a coordinated international ocean-atmosphere progr am that would highlight the response of global atmosphere circulation to long-period SST fluctuations in tropical regions. The unexpected arrival of the 1982-1983 El Niño demonstrated an urgency to establish an international program, which became TOGA. It is noteworthy that at the October 1982 conference, which was organized by Joseph Smagonnsky and convened at the NOAA GFDL to discuss the establishment of a new international ocean-atmosphere program, the attendees were unaware of the El Niiio which had begun three months earlier.

2.4 1982-1983 El Niño

By 1982, El Niño was considered to be a large-scale ocean-atmosphere phenomenon having important impacts upon global atmospheric circulation. Wyrtki (1975) had proposed that the onset is triggered by a relaxation of stronger-than-normal westward surface wind stress. Rasmussen and Carpenter (1982) had associated the average El Niño with a westward propagating sea surface temperature anomaly. Also, beginning in about 1979 satellite technology enabled sea surface temperature to be measured frequently and routinely throughout the tropical Pacific. Then, why did the onset of the 1982-1983 El Niño escape detection for several months? The easterly wind stress had not strengthened for a sufficiently long time interval; in fact, the easterly wind stress merely relaxed. The sea surface temperature anomaly did not move westward; it moved eastward. Anomalously high values of satellite-derived sea surface temperature measurements were discarded as false because El Chichón aerosols, which were produced in April 1982 and subsequent eruptions, greatly increased the uncertainty about the reliability of the new kind of measurement from satellite.

At the time of the 1982-1983 El Niiio, EPOCS and PEQUOD studies of equatorial wave dynamics were being conducted throughout the eastern and central equatorial Pacific. It was serendipitous that ocean circulation changes caused by El Niño were observed for the first time in the central and eastern Pacific far removed from land (Firing et *al.*, 1983; Halpern et *al.*, 1983; Toole and Borges, 1984), including effects on the biological environment (Feldman *et al.*, 1984). The magnitude of the observed variations associated with El Niño could be interpreted with respect to normal conditions because NORPAX and EPOCS had conducted studies of the annual cycle of oceanographic conditions. The first comprehensive collect ion of numerous oceanographic (biological, chemical and physical) and meteorological (including marine birds) results associated with the 1982-1983 El Niño was published during the El Niño in February 1983 in the *Tropical* " *Ocean-Atmosphere Newsletter*, which, at the time, had a worldwide distribution greater than 1300 recipients. During 1983 the anomalous atmospheric and oceanic events of 1982-1983 were reviewed in *Nature* (Philander, 1983; Gill and Rasmussen, 1983) and in *Science* (Barber and Chavez, 1983; Cane, 1983; Firing *et aL*, 1983; Halpern *et al.*, 1983; Rasmussen and Wallace, 1983). Almost immediately, the results of a very small group of investigators who happened to have the good scientific fortune to be involved in the largest El Niño in a century had reached a global audience with a new-found thirst for information about El Niño. The unusual worldwide environmental conditions that accompanied the El Niño were estimated to have caused agricultural, fisheries, and societal infrastructural damages of about $\$9 \times 10^9$ (1983 dollars) (Canby, 1984). The 1982-1983 El Niño episode represented an exciting intersection of scientific and societal objectives, which became the goal of TOGA: can science contribute to improved forecasts of El Niño.

The inability to adequately monitor the development of the 1982.-1983 El Niño caused a fundamental change at NOAA towards ocean science as then practiced in the equatorial Pacific, NOAA is the U. S. agency having primary responsibility to issue forecasts of weather and short-term climate variations. In December 1982, Joseph Fletcher, Director of EPOCS and Director of the NOM Environmental Research Laboratories, insisted to the EPOCS Council that never again should an El Niño occur unannounced or the meteorological and oceanographic community would risk losing a great deal of credibility. Thus, the policy for real-time monitoring of oceanographic and surface meteorological variables from moored and drifting buoys was firmly establish. To avoid repeating the situation in 1982 when data from mowed-buoy instruments were stored only inside the instrument and not electronically transmitted to shore, real-time transmission of moored-buoy wind and temperature measurements was begun in 1983 (Halpern et *al., 1984).* In addition, prediction of sea surface temperature variations in the central and eastern equatorial Pacific, i. e., prediction of warm events or El Niños, became a new subject of inquiry. Barnett (1984) was the first to show that the 1982-1983 El Niño could have been predicted 4-5 months in advance had information been available about the zonal wind component in the western Pacific.

In January 1983 the EPOCS Program commissioned a report to describe an oceanographic monitoring system for the eastern equatorial Pacific. The EPOCS Report (Halpern, 1983) indicated that real-time data acquisition from an array of instrumented surface moorings could monitor the generation and maintenance of El Niño anomalies associated with the surface wind, sea surface temperature, and upper ocean current and thermal fields. Figure 1 represents the El Niño detection system envisioned in March 1983. An important next step for detection of El Niño would be expansion of the moored array into the western Pacific, which was accomplished in 1985 through a joint U. S. and People's Republic of China (P. R. C.) bilateral agreement. I am pleased to have initiated discussions in 1982 for the joint U. S. - P. R. C. mooring at 0°, 165°E, where moored current measurements had been made for a few months in 1979 (Halpern, 1980).

Because of the sparseness of subsurface observations, progress to create operational descriptions of subsurface thermal and flow fields would have been extremely limited had not a reliable ocean general circulation model been developed (Philander and Seigel, 1985). Philander and Seigel (1985) were the frost to numerically simulate monthly mean sea surface temperature (and heat content and tropical current transports) variations over the tropical Pacific. This was a remarkable achievement because sea surface temperature represents the integration of atmospheric and oceanic dynamics and thermodynamics. Furthermore, researchers now had an ocean general circulation model for studies of equatorial circulation, including horizontal and vertical mesoscale features.

It has been known for a long time that a major uncertainty associated with simulation of equatorial ocean current and temperature fields is the representation or parameterization of turbulent mixing processes (Charney, 1960; McCreary, 1981). The Tropic Heat experiment was conducted in 1984 to determine space-time characteristics of vertical mixing processes in the central equatorial Pacific (Eriksen, 1985), including the representativeness of the Pacanowski and Philander (1981) parameterization of vertical mixing by turbulent processes, A second Tropic Heat experiment was made during TOGA. The tradition of process-oriented coupled ocean-atmosphere experiments in the equatorial zone, such as NORPAX, EPOCS, PEQUOD and Tropic Heat, was continued in TOGA because of a need to better understand the rich spectrum of oceanic and atmospheric motions to improve model simulations. For example, essential elements of the current system in the far western tropical Pacific were described by the Western Equatorial Pacific Ocean Circulation Studies (Lindstrom *et aL,* 1987). Parameterization of horizontal mixing, which is very poorly known and which could have important consequences upon simulation of upper ocean currents (Pacanowski and Philander, 1981), was an objective of the. Tropical Instability Wave Experiment (Qiao and Weisberg, 1995). The accurate determination of heat and fresh-water fluxes at the air-sea interface over the large pool of warm water in the western Pacific was a goal of the TOGA Coupled Ocean-Atmosphere Response Experiment (Webster and Lukas, 1992).

During the couple of years before the official start of TOGA, the foundations of the TOGA observing system and operational hindcasts of subsurface oceanographic conditions (Leetmaa and Ji, 1989) were established, and El Niño predictions (Barnett, 1984; Inoue and O'Brien, 1984) had begun. Soon after the start of TOGA, there was an opportunity to show that TOGA made a difference vis-a-vis El Niño prediction and monitoring. Predictions of the 1986-1987 El Niño had been made with varying levels of success (Cane *et al.,* 1986; Barnett *et al.,* 1988), which firmly established requirements for research on predictability of El Niño (Cane and Sarachik, 1991). In addition, monitoring the month-to-month pulse of the 1986-1987 El Niño (Halpern, 1989) amply demonstrated the success of the initial TOOA operational oceanographic system and established the need for a permanent ocean-atmosphere observing system, including research on effective methods for assimilation of satellite and in situ data.

Even before the official start of TOGA, the observing system involved participation from many countries. For several years before 1981, the Scientific Committee on Oceanic Research (SCOR) Working Group on the Global Weather Experiment provided the auspices for international cooperative studies of coupled large-scale long-period cxean-atmosphere studies in the -tropical Pacific. Internationality was continued from 1981 by the Pacific Ocean Climate Studies Panel of the Committee on Climatic Changes in the Ocean, which was jointly sponsored by SCOR and the Intergovernmental Oceanographic Commission. The sponsorship of TOGA by the World Meteorological Organization World Climate Research Program immediately expanded the international commitment with a greater involvement by the worldwide meteorological community.

3 TROPICAL ATLANTIC AND INDIAN OCEANS

Each tropical ocean basin has unique characteristics of geography and environmental conditions, and the development of tropical ocean models demanded oceanographic data from each basin (Philander, 1990). In 1974, the 3-month Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) revealed that ocean variability at submonthly time scales was associated with zonal wave lengths of approximatel y 1000 km (Düing *et al.*, 1975). A similar phenomenon was observed in the Pacific soon afterwards (Legeckis, 1977). The much larger spatial scales of mesoscale ocean variability in tropical lath udes compared to those in middle latitudes simplified the design of tropical oceanographic measurement arrays. In the western North Indian Ocean, ocean dynamics are strongly influenced by intense monsoon wind forcing (Schott, 1983). Because of the different sizes of the tropical Atlant ic and Pacific ocean basins, the annual cycle in the Atlantic is expected to be of larger amplitude than that in the Pacific and the magnitude of interannual variations in the Pacific is expected to be of larger amplitude compared to that in the Atlantic (Philander, 1979). The 1983-1984 Seasonal Response of the Equatorial Atlantic (SEQUAL) and Programme Français Océan et Climat clans l'Atlantique Equatorial (FOCAL) programs confirmed that the annual cycle is the dominant time scale throughout the tropical Atlantic (Katz, 1987; Richardson and Reverdin, 1987). By the beginning of TOGA, the essential time and space scales of tropical ocean circulation had been described and, in most instances, understood well enough to be reproduced in theoretical and numerical models (Knox and Anderson, 1985). However, the relative importance of heat advection by ocean currents in seasonal-to-interannual variations of tropical SST was unknown at the start of TOGA and became a TOGA objective.

4 EQUATORIAL CURRENT MEASUREMENT TECHNOLOGY

In the context of the historical development of TOGA, the Equatorial Undercurrent (EUC) represents an environmental barrier for continuous measurements of upper ocean current and temperature and surface wind in order to detect El Niño conditions. The engineering difficulty in maintaining a surface mooring on the equator in water depths of 4-5 km arises from the stresses on the mooring line created by the shears of strong currents in the upper ocean. In the Pacific, the eastward-flowing EUC has a maximum speed greater than 1 m s^{-1} at about 100 m depth and occurs beneath the westward-flowing South Equatorial Current, which has a speed of more than 1 m s^{-1} at the surface. The difficulty to record time-series measurements beneath a surface buoy moored at the equator was demonstrated in 1971 by Taft *et al.* (1974). The difficulty was overcome by adding fairing to the upper 300 m of the mooring line.

The first Pacific-wide array of tautly-moored surface buoys, each of which had 5-7 current meters above 250 m depth, was established in 1979 when upper ocean temperature and current measurements were recorded along the equator at 165°E, 152°W and 110°W (Halpern, 1980). By the start of TOGA, the technology to record reliable surface wind and other meteorological variables and upper ocean current and temperature observations continuously for long periods at the equator had been employed in the Atlantic during FOCAL-SEQUAL (Weisberg, 1984) and in the Pacific during EPOCS and NORPAX. For example, at the equator and 110°W, moored current measurements at several depths in the upper ocean were continuously recorded from 1980 to the start of TOGA (Halpern, 1987) and throughout TOGA (McPhaden and McCarty, 1992), which has created the longest time series of upper-ocean current measurements in the world.

5 SUMMARY

TOGA focused on the El Niño Southern Oscillation phenomenon and conducted research on the coupled ocean-atmosphere system, observing network design, data assimilation, model development, and prediction. The word "coupled", as in "coupled ocean-atmosphere system", is significant because pre-TOGA research focused on the uncoupled ocean and uncoupled atmosphere systems. Twenty yearn before TOGA, Bjerknes (1966) had proposed a conceptual model of the coupled tropical ocean and global atmosphere system, but it was not until the beginning of TOGA that sufficient knowledge had been accumulated about dynamics of low-latitude ocean circulation and dynamics of the atmosphere for coupled ocean-atmosphere model simulations to yield encouraging results. Large-scale coupled ocean-atmosphere interactions has become a new field of scientific inquiry, with problems unique to the specialty. For example, one of the lessons learned by TOGA is that coupled ocean-atmosphere general circulation model simulations of SST along the Pacific equator are less representative compared to observations than SST simulated from uncoupled ocean general circulation models (Mechoso *et al.*, 1995).

That TOGA accomplished the objectives stated at the start of the program is one measure of its success. Scientific objectives were attainable because of previous scientific and engineering accomplishments. That scientific objectives were associated with an internationally societal-relevant phenomenon is very important for a program designed to last for many years, especially when the time scale of financial support to investigators is less than the duration of the program. Legacies created by TOGA are: operational subsurface oceanography y, including free and rapid distribution of all data and model results; seasonal-to-interannual predictions of oceanographic and meteorological conditions; improved understanding and model parameterization of sub-grid size scale processes in the tropical atmosphere and ocean; an international effort to apply El Niño predictions for the benefit of societies (Moura, 1992); and an approximate ten-fold increase in the number of researchers involved in TOGA-type research (which I estimated from the attendance at the International TOGA 95 Scientific Conference in April 1995 in Melbourne, Australia). TOGA legacies are foundations for future programs.

Tropical Pacific sea surface temperature is one of many variables that influence global atmospheric circulation (Shukla, 1985). The degrees of predictability of seasonal-to-interannual global atmospheric circulation variability caused by different boundary forcings, such as anomalies of sea surface temperature, soil moisture, sea ice, snow, etc., has become a leading objective of a post-TOGA program, named Climate Variability and Predictability and which in the U. S. is known as Global Ocean-Atmosphere-Land S ystem (GOALS) for Predict ing Seasonal-to-Interannual Climate (NRC, 1994).

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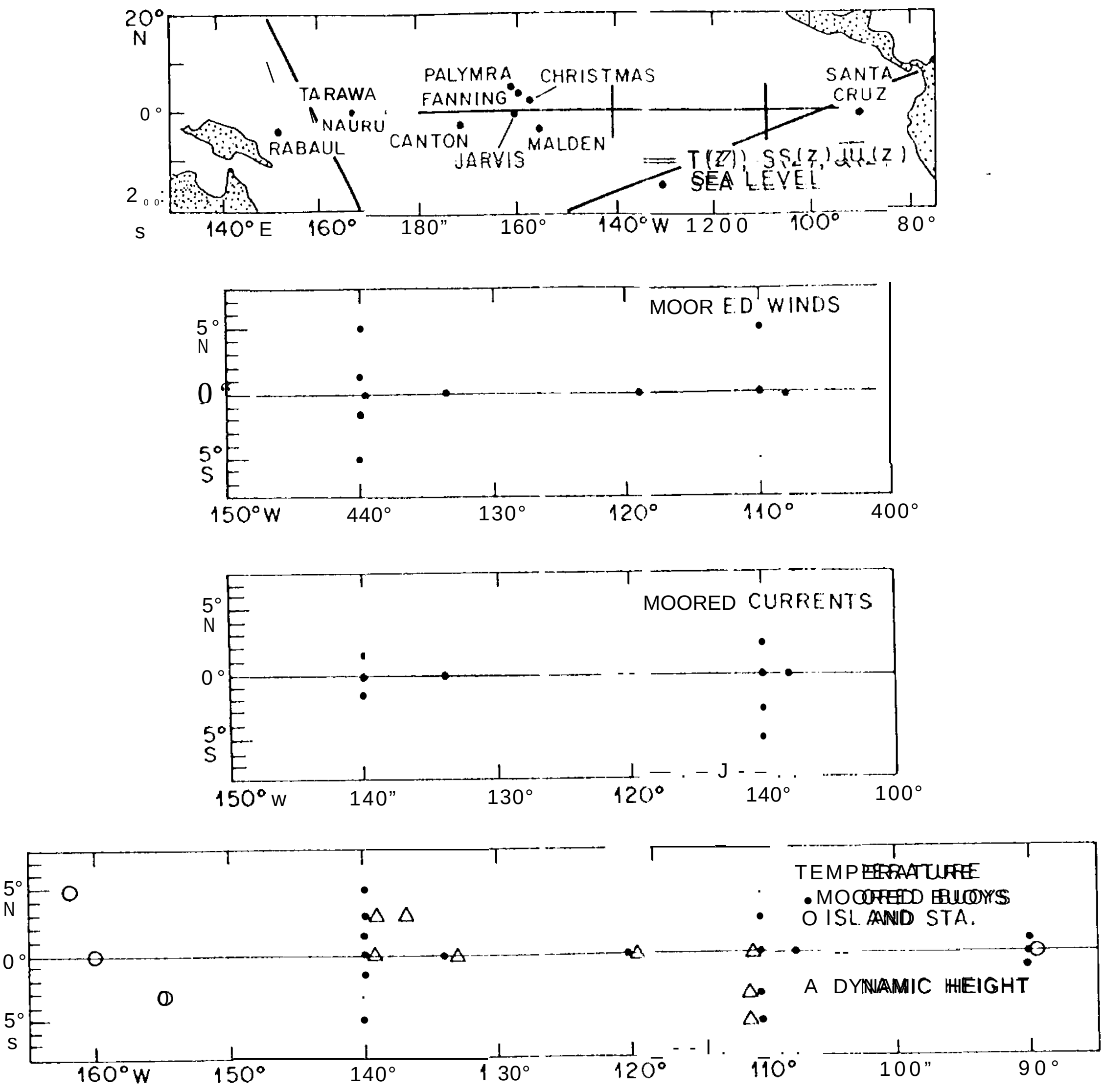
Table 1. Scientific objectives of the TOGA Program (WMO, 1985).

(1) To gain a description of the tropical oceans and the global atmosphere as a time-dependent system in order to determine the extent to which the system is predictable on time scales of months to years, and to understand the mechanisms and processes underlying its predictability;

(2) To study the feasibility of modeling the coupled ocean-atmosphere system for the pin-pose of predicting its variations on time scales of months to years; and

(3) To provide the scientific background for designing an observing and data transmission system for operational prediction if this capability is demonstrated by coupled ocean-atmosphere models.

Figure 1. Elements of the El Niño detection system described in the EPOCS Report (Halpern, 1983). Solid lines drawn in upper panel represent ship-of-opportunity XBT or research vessel CTD (conductivity y-temperature-depth) and ADCP (acoustic doppler current profiler) lines.



PALYMRA
CHRISTMAS
FANNING
TARAWA
NAURU
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JARVIS
MALDEN
SANTA CRUZ
SEA LEVEL
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MOORED WINDS
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O ISLAND STA.
DYNAMIC HEIGHT
150°W
160°W
150°
140°
130°
120°
110°
100°
90°